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Influence of Environmental Temperature on 40 km Cycling Time-Trial Performance

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The purpose of this study was to examine the effect of environmental temperature on variability in power output, self-selected pacing strategies, and performance during a prolonged cycling time trial. Nine trained male cyclists randomly completed four 40 km cycling time trials in an environmental chamber at 17°C, 22°C, 27°C, and 32°C (40% RH). During the time trials, heart rate, core body temperature, and power output were recorded. The variability in power output was assessed with the use of exposure variation analysis. Mean 40 km power output was significantly lower during 32°C (309 ± 35 W) compared with 17°C (329 ± 31 W), 22°C (324 ± 34 W), and 27°C (322 ± 32 W). In addition, greater variability in power production was observed at 32°C compared with 17°C, as evidenced by a lower ($P = .03$) standard deviation of the exposure variation matrix (2.9 ± 0.5 vs 3.5 ± 0.4 units, respectively). Core temperature was greater ($P < .05$) at 32°C compared with 17°C and 22°C from 30 to 40 km, and the rate of rise in core temperature throughout the 40 km time trial was greater ($P < .05$) at 32°C (0.06 ± 0.04°C·km^{-1}) compared with 17°C (0.05 ± 0.05°C·km^{-1}). This study showed that time-trial performance is reduced under hot environmental conditions, and is associated with a shift in the composition of power output. These finding provide insight into the control of pacing strategies during exercise in the heat.

Keywords: thermoregulation, cyclist, heat, pacing, exposure variation analysis

Prolonged exercise in the heat is associated with a significant increase in core body temperature,[1–3] resulting in an increase in perceived fatigue,[1,4] and a decrease in exercise performance.[5–8] Indeed, decreases in cycling time to fatigue[2,6] and average time-trial power output[1,8,9] have been observed in hot (>30°C) compared with cool (<21°C) conditions. These decreases in performance during exercise in the heat are likely due to an anticipatory reduction in intensity mediated by the central nervous system, possibly in response to the rate of rise in core temperature.[8,10] Further, it has been suggested that exercise intensity during self-paced exercise is continu-

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ously regulated, in response to factors such as afferent sensory feedback and prior experience and motivation, to ensure that performance is optimized.[11] Thus, minor fluctuations in power output or work rate that occur throughout an exercise task may be evidence for a central regulation of exercise intensity.[11] Despite this, the impact of hyperthermic stress on variability in power output, fatigue development, and self-selected pacing strategies during endurance cycling remains unclear. Much of this uncertainty may be attributed to the fact that the majority of previous studies examining the effects of temperature on self-selected pacing strategies typically conducted trials in only extreme hot and/or cool conditions.[1,8] Since it is unlikely that performance during exercise in cool environmental conditions is limited by thermoregulatory stress, studies examining relationships between pacing, performance, and body temperature at such extreme temperatures are somewhat limited.[12] In order to gain a greater understanding of the role of thermoregulation in fatigue development and pacing during prolonged exercise, research examining the effect of temperature on exercise performance beyond very hot versus cold is warranted.

Few studies have examined the influence of environmental temperature on performance in a variety of environmental conditions.[10,13,14] Galloway and Maughan[14] examined the effect of a range of environmental conditions on time-to-fatigue when cycling at a fixed power output (70% of VO_2max) and observed the greatest time to fatigue to occur at 11°C (compared with 4°C, 21°C, and 31°C). However, in this study, power output was fixed and thus the influence of temperature on pacing strategy could not be assessed. Furthermore, the air velocity used was considerably lower than that experienced during actual competitive cycling (2.5 $km \cdot h^{-1}$ vs >40 $km \cdot h^{-1}$), which can have a significant influence on the rate of rise in core body temperature during exercise.[15] Consequently, no study has yet examined the influence of changes in body temperature on self-paced cycling time-trial performance at a variety of environmental conditions.

Therefore, the purpose of the present study was to determine the influence of a range of environmental temperatures (17–32°C) on 40 km time-trial performance, and the individual pacing strategies during these time trials.

Methods

Participants

Nine male cyclists (age: 35 ± 7 y, height: 183 ± 7 cm, mass: 80.3 ± 9.7 kg, VO_2max 60.5 ± 4.5 $mL \cdot kg^{-1} \cdot min^{-1}$, peak power: 441 ± 32 W) volunteered to complete one graded exercise test and four 40 km cycling time trials. Sessions were separated by no less than 5 d and no greater than 14 d, with all trials performed at a similar time of day. All participants had previously volunteered for studies within our laboratory using the same equipment and completing time trials of a similar distance under hot conditions. Further, to decrease the likelihood of heat acclimatization influencing the time trial results, this study was conducted during the summer months (mean outside temperature: 31.0 ± 1.0°C). Participants were instructed to avoid strenuous physical activity the 24 h preceding each test. In addition, participants were asked to consume a similar diet the night before and the day of each session. Participants were informed of the possible risks and benefits of participation in this study, and a written informed consent was obtained from the participants before data collection. Ethical clearance was obtained from the necessary university research ethics committee before the commencement of this study.

Graded Exercise Test

During the initial testing session, participants completed a graded exercise test on an electromagnetically braked cycle ergometer (Velotron Racermate, Seattle, USA) at room temperature (22°C). During this test, participants began cycling at 70 W for 1 min after which power output increased 35 $W \cdot min^{-1}$ until volitional fatigue. After completing the graded exercise test participants were asked to cycle for an additional 20 min to further familiarize themselves with the Velotron cycle ergometer. During this time, participants were asked to frequently alter the gear ratio in order to become accustomed with the electronic control unit and simulated gear ratios of the Velotron cycle ergometer.

Experimental Trials

During the remaining experimental trials participants completed four 40 km cycling time trials in an environmental chamber maintained at 17, 22, 27, or 32°C and 40% relative humidity (RH). The cycle ergometer was adjusted to mimic each participants own bicycle and this bike positioning was kept constant throughout the four experimental trials. Experimental trials were conducted in a counterbalanced order. Before the start of exercise, participants self-inserted a rectal thermometer (Monatherm Thermistor, 400 Series; Mallinckrodt Medical, USA) 12 cm past the anal sphincter and were fitted with a Polar heart rate monitor (810i, PolarElectro, Kempele, Finland). Before each test, the participants completed a 5 min warm-up after which they were allowed 5 min of rest before starting the 40 km time trial. Participants were instructed to complete the time trial as fast as possible. No verbal encouragement was given to the participants during the time trials and participants were only provided feedback on the total distance completed. Ratings of perceived exertion (RPE; 10, 20, 30, and 40 km) and thermal sensation (TS; 10, 20, and 30 km) were recorded using 10 point visual analog scales.[16,17] In addition, a large fan providing a wind speed of 32 $km \cdot h^{-1}$ was placed directly in front (approx. 1 m) of the subjects and started upon commencement of each trial.

Data Processing

During the time trial, power output was recorded at a frequency of 1 Hz (Velotron Coaching Software, Racermate, Seattle, USA) and averaged over each 5 km. In addition, the average power output for the entire 40 km time trial was recorded for analysis. Heart rate was recorded at a beat-by-beat frequency and rectal temperature was recorded at a frequency of 1 Hz using a data logger (Grant Instruments, Cambridge, UK). Both heart rate and rectal temperature measurements were converted to 5 km averages to coincide with the power output measurements. In addition, the rate of change in rectal temperatures during each 5 km section was calculated.

To further investigate the effect of ambient temperature on pacing, raw (1 Hz) power output data were analyzed using exposure variation analysis, as previously described.[18] In brief, exposure variation analysis was used to quantify the time and amplitude domains of the participant's power output as an expression of the overall time-trial time. To accomplish this, individualized power bands were calculated for each participant and condition (17, 22, 27, and 32°C). Five power bands were calculated from the average power output of each trial (–10%, –5%, 0% [average power], +5%, and +10%) and the total amount of time within each power band was recorded. In addition, the total time in each power band was further separated by the frequency of occurrence in six predetermined time domains (0–3.75 s, 3.75–7.5 s, 7.5–15 s, 15–30 s, 30–60 s, and 60+ s), which were selected based on previous research in elite female time trialists.[18] To assess the exposure variance analysis matrix, the total standard deviation of the matrix was calculated. A greater standard deviation is associated with greater monotony of measurement and less-even dispersion of power output (Figure 1).[19]

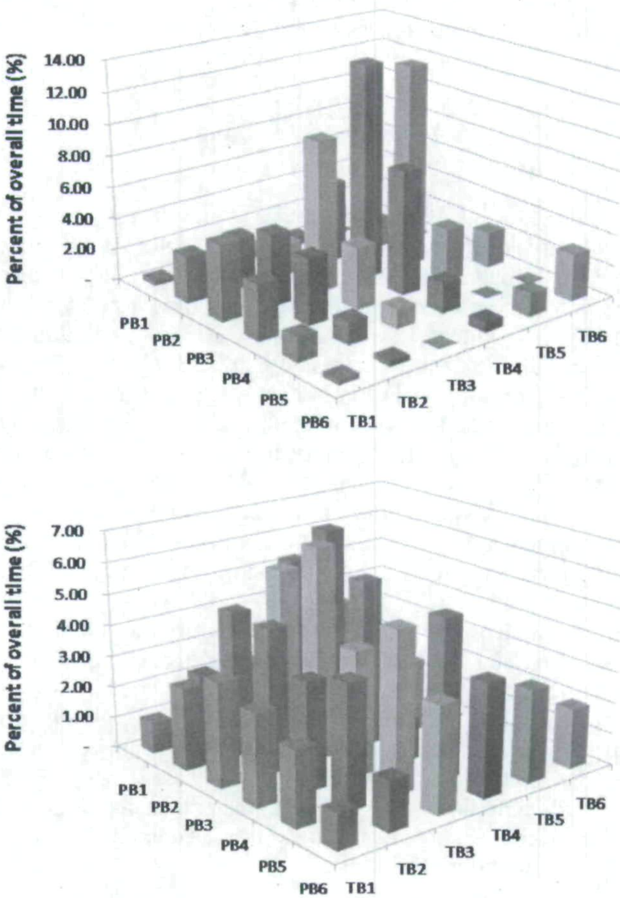

Figure 1 — Composition of the mean power output measured during a 40 km time trial at 17°C (top) and 32°C (bottom) for a single individual calculated using exposure variation analysis.

Statistical Analysis

Differences in power output, heart rate, rectal temperature, RPE, and TS between environmental conditions were analyzed using a two-way analysis of variance (ANOVA), with repeated measures. Significant main effects and interactions were analyzed using a Tukey HSD post hoc test. The difference in the total mean power output between the 40 km time trials and the standard deviation of the exposure variance analysis matrix were analyzed with a one-way ANOVA. A Pearson product correlation coefficient was calculated between the mean 40 km time-trial power output and the mean rate of rise for each condition. In addition, the percent change in mean power between each condition was compared using the smallest worthwhile performance difference (1.0%) calculated from previously published coefficient of variation measurements of sustainable power during a time trial using the Velotron cycle ergometer.[20–22] All statistics were completed using Statistica (Version 7; Stat-Soft, Tulsa, USA) with the level of significance set to $P < .05$. Data are presented as means ± standard deviations, unless otherwise noted.

Results

40 km Performance

Mean power output over the 40 km time trial was significantly different between conditions with a greater mean power in the 17°C (329 ± 31 W; $P < .01$), 22°C (324 ± 34 W; $P < .01$), and 27°C (322 ± 32 W; $P = .01$) conditions compared with the 32°C condition (309 ± 35 W). Further, the total time needed to complete the 40 km time trial was significantly greater in the 32°C (60.7 ± 2.9 min) condition compared with the 17°C (58.8 ± 2.0 min; $P < .01$), 22°C (59.0 ± 2.3 min; $P < .01$), and 27°C (59.1 ± 2.3 min; $P < .01$) conditions. A significant interaction ($P < .01$) was observed for the mean 5 km power output measurements between conditions (Figure 2a). A significantly greater 5 km mean power output was observed in the 17°C condition at 25 km compared with the 27°C condition, and from 15 to 40 km compared with the 32°C condition. In the 22°C condition, mean 5 km power output was greater than in the 32°C condition from 20 to 40 km. Mean 5 km power was significantly greater in the 27°C condition compared with the 32°C condition from 30 to 40 km.

A significant interaction ($P = .02$) was observed for the standard deviation of the exposure variation analysis data. The mean standard deviation was significantly less ($P = .04$) during 32°C (2.9 ± 0.5 units) compared with the 17°C (3.5 ± 0.4 units) condition, indicating a greater monotony of power at 17°C. No other differences in the standard deviation of the exposure variation analysis were noted between the 22°C (3.3 ± 0.6 units) or 27°C (3.0 ± 0.4 units) trials.

The percent difference in mean power was greater than the smallest worthwhile change in performance (1%) between all conditions, except 22°C versus 27°C and 17°C versus 22°C conditions (Figure 3).

Rectal Temperature

A significant interaction ($P < .01$) between rectal temperature over each 5 km and environmental condition was observed (Figure 2c). Rectal temperature was signifi-

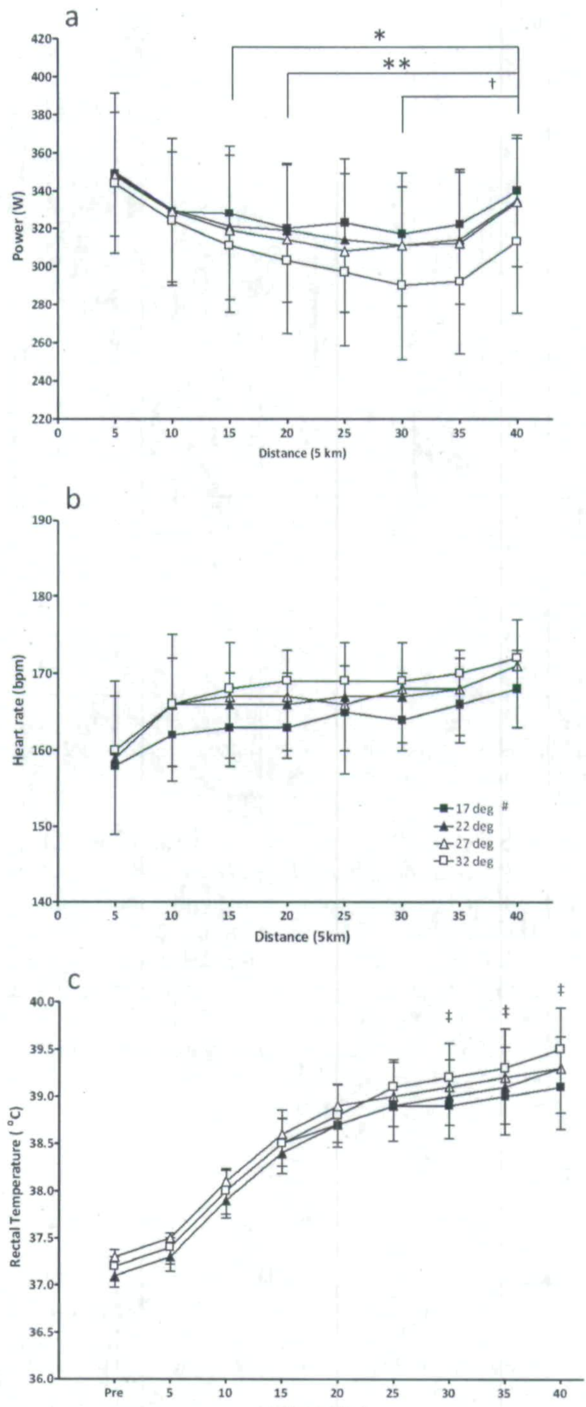

Figure 2 — Mean power output (a), heart rate (b), and rectal temperature (c) over each 5 km during a 40 km time trial at 17, 22, 27, and 32°C (40% relative humidity). *Significant difference 17°C vs 32°C. **Significant difference 22°C vs 32°C. †Significant difference 27°C vs 32°C. ‡ Significant difference 32°C vs 17°C and 22°C.

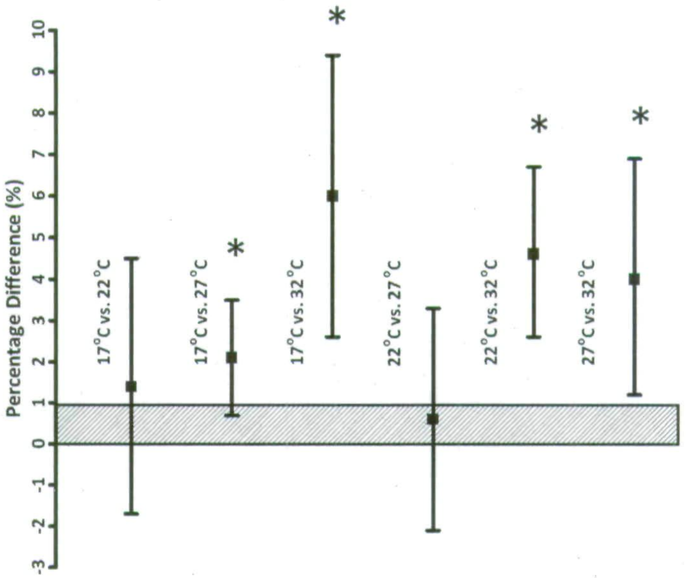

Figure 3 — Percent difference (%; ± 95% confidence intervals) in 40 km mean power between 17, 22, 27, and 32°C conditions. *Difference likely to affect performance. Filled bar = smallest worthwhile change in performance.

cantly greater in the 32°C condition compared with the 17°C and 22°C conditions from 30 to 40 km; however, no other differences were observed between conditions or at any other time points. In addition, a significant condition ($P = .04$) and time effect ($P < .01$) was observed for the 5 km rate of rise in rectal temperature (Figure 4). The rate of rise in rectal temperature was significantly greater at 10 and 15 km compared with all other time points. Further, the mean rate of rise over the 40 km time trial was significantly greater ($P = .03$) at 32°C (0.06 ± 0.04 °C·km^{-1}) compared with 17°C (0.05 ± 0.05 °C·km^{-1}). A negative correlation ($r = -0.93$) was observed between the mean rate of rise in core temperature compared with mean 40 km power output between conditions.

Heart Rate

Both a condition ($P = .03$) and time effect ($P < .01$) were observed for the 5 km mean heart rate data (Figure 2b). The heart rate measured at 5 and 10 km was significantly lower compared with values measured between 15 and 40 km. Between conditions, heart rate was significantly greater ($P = .02$) in the 32°C (168 ± 10 bpm) condition compared with the 17°C (164 ± 7 bpm) condition; however, no other differences between conditions were observed.

RPE and TS

Differences in RPE and the TS measures between conditions and over time are shown in Table 1. In all conditions, RPE was greater at 20 and 30, and 40 km compared with 10 km. Additionally, TS was greater at 30 km compared with 10

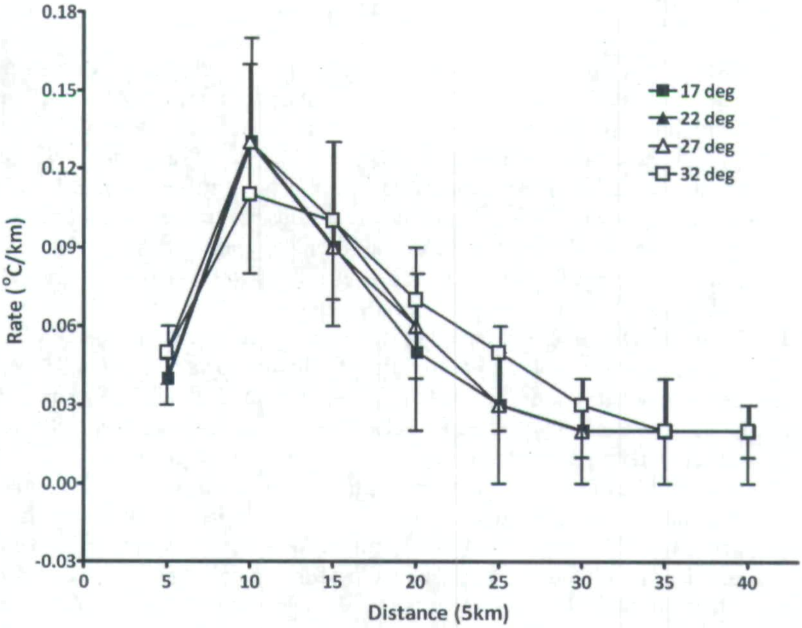

Figure 4 — Rate of change in rectal temperature over each 5 km during a 40 km time trial at 17, 22, 27, and 32°C (40% relative humidity).

and 20 km for all conditions. Further, a significant condition effect ($P < .01$) was evident for TS with greater average values measured in the 32°C condition (5.9 ± 0.7 units) compared with the 17°C (3.7 ± 1.0 units; $P < .01$), 22°C (4.5 ± 0.8 units; $P < .01$), and 27°C (4.8 ± 0.9 units; $P < .01$) conditions. Finally, a significant condition effect ($P < .01$) was observed for RPE scores with a greater average RPE for the 32°C condition (17.1 ±1.5 units) compared with the 17°C (15.8 ± 1.5 units; $P < .01$) and 27°C (16.1 ± 1.3 units; $P = .02$) conditions.

Table 1 Ratings of perceived exertion (RPE) and thermal sensation (TS) measured at 10, 20, 30, and 40 km during a 40 km time-trial at 17, 22, 27, or 32°C and 40% relative humidity

	RPE*‡				TS**†		
	10 km	20 km	30 km	40 km	10 km	20 km	30 km
17°C	15.2 ± 1.8	16.3 ± 1.3	16.4 ± 1.2	20	3.3 ± 1.0	3.6 ± 0.9	3.9 ± 1.1
22°C	15.7 ± 1.7	16.4 ± 1.6	16.7 ± 1.2	20	4.2 ± 0.5	4.5 ± 0.7	4.7 ± 0.9
27°C	15.4 ± 1.2	16.5 ± 1.4	16.8 ± 0.8	20	4.8 ± 0.8	5.0 ± 0.9	5.0 ± 1.1
32°C	16.2 ± 1.8	16.9 ± 1.6	17.4 ± 1.2	20	5.3 ± 0.8	5.8 ± 0.8	6.2 ± 0.9

Note. No TS data measured at 40 km. All participants indicated a RPE of 20 at completion of all trials. *Main effect for time, 20 and 30 km > 10 km. **Main effect for time, 30 km > 10 and 20 km. †Main effect for condition, 32°C > 17°C, 22°C, and 27°C. ‡Main effect for condition, 32°C > 17°C and 27°C.

Discussion

The purpose of this study was to examine the pacing strategies and overall performance of cyclists performing a 40 km time trial under a range (17, 22, 27, and 32°C) of ambient temperatures. The main findings from this study are that (1) the average power output was significantly greater in the 17, 22, and 27°C trials compared with the 32°C trial; (2) the overall pacing strategy was similar between conditions, although the decline in power output observed after commencement of the trials, occurred earlier in the 32°C condition compared with the 17, 22, and 27°C conditions; and (3) the variation in power output was found to be greater in hot (32°C) compared with cool (17°C) conditions.

It is well accepted that endurance performance is reduced during exercise in the heat.[3,5,6,8,9] Indeed, we observed significantly lower power output and greater completion times during the time trial at 32°C compared with 17°C, 22°C, and 27°C. Our findings are consistent with data from Galloway and Maughan[14] who observed a significant decrease in time to fatigue during cycling at 31°C compared with 4°C, 11°C, and 21°C, and further complement the findings of Galloway and Maughan[14] by providing additional information on the effect of environmental temperature on self-paced work. We acknowledge that our study is not the first to examine the effect of ambient temperature on self-paced performance;[1,8,9] however, our study is the first to systematically examine a range of environmental conditions on self-paced exercise performance in a single group of athletes, thus presenting a clear indication of the effects of environmental temperature on endurance performance.

In addition to traditional statistical analysis we also compared changes in performance between conditions to the smallest worthwhile change necessary for performance enhancement.[21] This method of analysis allows for the theoretical indication that changes in mean power output, albeit small (ie, 5.0 W between the 17°C and 22°C trial), would have on cycling time-trial performance.[21,23] Our findings indicate a decrease in 40 km cycling time-trial performance with increasing environmental temperature, with the exceptions of the 22°C compared with 27°C, and the 17°C compared with the 22°C conditions (Figure 3). These findings should be of interest to cyclists who regularly compete in the time-trial discipline; however, it should be acknowledged that in a true competitive environment performance may be influence by addition factors (ie, training status and race tactics).

The overall pacing strategy observed in this study was remarkably similar in all conditions and was categorized by a progressive reduction of power during the middle portion of the time trial followed by a late trial increase in power production (Figure 2a). This pacing strategy is common and has previously been observed in rowing,[24] running and cycling endurance events,[1,8] in addition to shorter higher intensity cycling exercise.[25,26] In the heat, an anticipatory reduction in power output elicited by increasing core temperature,[8] and/or a greater thermal sensation experience by the cyclist[27] has been suggested to explain this type of pacing strategy. In our study, we observed a significantly greater overall rate of rise in core temperature (Figure 4) and a higher thermal sensation (Table 1) at 32°C compared with 17°C, which was associated with lower mean power output at 32°C compared with 17°C. Further, our data indicates a high level of association ($r = -0.93$) between the total rate of rise in core temperature and mean 40 km time-trial power output. A great deal of debate exists as to the exact mechanisms responsible for the manipulation of power output during fatiguing exercise[28] with evidence supporting both central and peripheral control. It is likely that both central and peripheral influences control power output during exercise in the heat as increases in body temperature would result in afferent feedback to the brain[8] producing a cognitive manipulation of locomotion to decrease heat production and maintain a tolerable exercise environment. Indeed, the observation of higher power output in the final 5 km split of all trials in the present study (ie, “end spurt”), despite a continued decrease in power production throughout the 40 km time trial (Figure 2a), indicates the lack of total fatigue at the muscular level, providing evidence for a cognitive manipulation of power output.[29]

In addition to measuring mean power output, we further examine the influence of ambient temperature on pacing strategies using exposure variation analysis. It has been suggested that minor fluctuations in power output or work rate observed throughout an exercise bout may be evidence for a central regulation of exercise intensity.[11] Within this hypothesis it is believed that neural drive and thus muscle recruitment is continuously altered in response to afferent feedback from peripheral physiological systems.[11] As such power output tends to oscillate in a seemingly random manner throughout an exercise bout. During a time trial, however, the need for a constant high power output typically results in a low variability in power, or a high level of monotony.[18] Indeed, during prolonged cycling time trials performed in laboratory conditions (ie, without hills or headwinds) performance is optimized with the adoption of a constant/even pacing strategy.[30] Regardless, an increase in afferent feedback to the brain,[11] decrease in arousal,[4] and/or a reduction in central activation[31,32] during periods of high physiological stress (ie, exercise in the heat) might increase the variability in power output. In the present study, we observed a higher standard deviation in the exposure variation matrix of power output during the 17°C, compared with the 32°C condition, which indicates that a greater percentage time was spent within a particular intensity/duration band and therefore represents a more monotonous distribution of power output. Conversely, the low standard deviation observed in the 32°C trial indicates that power output was distributed throughout the range of intensity/duration bands and thus represents a variable intensity. Consequently, it appears that decreases in performance observed at high environmental temperatures are associated with a less monotonous or more variable power output. To our knowledge, we are the first to show such an inconsistency in the method of power production during a time trial at different ambient temperatures and this difference may provide insight into the mechanisms that control pacing during exercise in the heat.

Based on previous studies examining pacing strategies[5] and exposure variation analysis from the current study, it would appear that athletes should attempt to reduce minor variations in power output during exercise in the heat in order to improve overall performance. However, as previously mentioned, such increases in the variability of power output during exercise in hot environmental conditions reflects an increase in fatigue associated with an greater afferent feedback and/or a decrease in central drive. This afferent feedback is likely to play a significant role in the self-regulation of power output during exercise. Consciously overriding sensations of fatigue and attempting to minimize variations in power output may place additional stress on various physiological systems resulting in greater localized fatigue development and reduced performance. As such, it is unclear from this study whether the increase in the variations of power output observed in the heat is advantageous or detrimental to overall performance. Further research examining the influence of minor fluctuations on performance is warranted.

The findings from the present study add to the growing body of knowledge regarding exercise in the heat. Nevertheless, we acknowledge that due to our selected methodology and specific aims of this study, there may be possible limitations with our findings. Without the measurement of hydration status, we cannot confirm or deny that the level of hydration was not a factor influencing our performance results. Nevertheless, we believe that while the addition of a hydration measure would have provided a greater insight into the mechanisms behind the differences in performance observed in this study, its exclusion did not deter from examining the influence of environmental temperature on 40 km cycling performance and thus achieving the primary aim of this study.

Practical Applications

Within the sport of cycling, the chance of success during a time trial may be decided by only a few seconds between riders. Therefore, even small differences in performance between individuals during a time trial are important. Our data indicates that shifts in ambient temperatures can alter performance during a 40 km time trial and the influence of ambient temperature on performance should be a concern of both cyclists and coaches. In addition, we have shown that composition of power output during self-selected pacing is altered during exercise in the heat (≥32°C). While it is not know if the changes in the composition of power output are a consequence of fatigue or assist in delaying its onset, our findings may provide a useful means to examine fatigue in sport.

Conclusion

In summary, our data indicate that a statistically significant decrease in sustainable time-trial power can occur in very hot (>32°C) conditions. Further, differences in the mean power output between the 17°C and 32°C conditions was associated with a greater variability in the composition of power production at the higher temperature, and this finding may present a new method for analyzing fatigue during exercise in the heat. Both the change in mean power output and composition were likely attributed to a greater rate of rise in core body temperature and thermal sensation when exercising in the heat; thus, resulting in an anticipatory reduction in performance.

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